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Evaluating the mix of maintenance activities on railway crossings with respect to life-cycle costs

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Abstract

Switches & crossings (S&Cs) are vital assets as they allow for increased railway capacity by introducing flexibility and connectivity in railway networks. At the same time, this makes them critical since they can cause costly delays and disruptions if they are not well maintained. This motivates studies to improve maintenance strategies of S&Cs, considering both the life-cycle costs (LCCs) of the assets and socio-economic transportation costs for passengers and freight customers. In this paper, the interdependence between deterioration mechanisms, maintenance activities, and expected LCC (including transportation costs) for the crossing panel – an S&C subsystem – is investigated using a combination of mechanical and econometric modelling. The interrelation between the degradation of contact geometry and track settlement is analysed using simulations of dynamic vehicle–turnout interaction. Long-term mechanical degradation of the crossing panel is simulated for different maintenance strategies that correspond to different timing of the associated maintenance measures (crossing repair welding and tamping). This provides the basis for analysing the interdependence between preventive and corrective activities using econometric modelling. Based on a case study of a common type of S&Cs in the Swedish infrastructure, the impact of different maintenance strategies on LCC and transportation costs is analysed. Opportunities and challenges in the development of more economically effective maintenance strategies of S&Cs are discussed.

1 Introduction

Switches & crossings (S&Cs) are assets that allow trains to change from one track to the other. This creates flexibility and connectivity in the network, which in turn facilitates an increase in railway capacity. An effective maintenance strategy for S&Cs is generally chosen with respect to various factors such as S&C characteristics and capability, traffic load, safety standards, maintenance costs, and budget restrictions (Stenström et al., 2016).

According to the Swedish rail infrastructure manager Trafikverket (2022), the state-owned network comprises around 14,200 km and includes around 11,400 S&Cs, i.e., a density of 0.8 S&C per km. Based on the Swedish transport appraisal guidelines (Trafikverket, 2020a), the maintenance and renewal of S&Cs comprise up to 90,000 SEK[1] and 4.5 million SEK per S&C and year, respectively (2017 price level). There can also be transportation costs due to traffic disruptions and delays caused by, for instance, a failure in one of the S&C components (Lidén, 2019).

Hence, from society's point of view, the net present value of socio-economic costs and benefits is an important yardstick for the maintenance strategies of S&Cs and their components. Several studies have attempted to assess the long-term costs of these strategies using one (or a combination) of different existing approaches such as engineering (Li et al., 2014) or lifecycle cost (LCC) studies (Nissen, 2009b). However, there is a lack of research on the impact of changing the mix of maintenance activities, and thus how strategies compare against each other.

The purpose of this paper is to analyse the impact of a change in the mix of maintenance activities on railway crossing panels. The aim is to show how maintenance strategies can be compared with respect to their LCC, including their main transportation costs for passengers and freight customers.

The analysis consists of three steps. First, simulations based on engineering methods are carried out to analyse the impact on ballast settlement and tamping needs for two scenarios, one where the crossing geometry is allowed to deteriorate to an extreme condition, and one scenario where the crossing geometry is well-maintained. The aim is to provide a basis for the trade-off between preventive and corrective maintenance, but also give insights into the dependencies between different deterioration modes and how they are influenced by different maintenance activities. Second, the impact of preventive (condition-based) maintenance on corrective maintenance is evaluated based on data from the Swedish railway network using econometric methods. Third, with a focus on a selected S&C and its crossing panel, results from the econometric estimations are used in an LCC calculation example, which also includes the socio-economic consequences for traffic, and compares the effectiveness of different maintenance strategies. For this demonstration case, LCC is not evaluated based on results from the simulation model. The calibration of the mechanical simulation model against field measurement data for this specific S&C to establish its digital representation (a so-called digital twin) is, however, a natural next step in this research.

Existing research on long-term maintenance of rail infrastructure has adopted econometric, engineering methods, and/or lifecycle costing. Econometric studies assess traffic-cost relationships, mechanical models focus on deterioration mechanisms, while lifecycle costing considers economic aspects throughout an asset's life. However, few studies combine these methods to investigate the long-term maintenance planning of specific rail asset components such as S&Cs and crossing panels, see the literature review in Section 2 for a more elaborate review of existing works. This paper fills this gap by combining qualitative results of mechanical simulations with empirical analysis of the interplay between preventive and corrective maintenance activities. By focusing on the crossing panel of a selected S&C, it is illustrated how different maintenance mixes can be compared in terms of LCC for more effective long-term maintenance decisions.

The literature is briefly reviewed in Section 2. In Section 3, relevant information on the maintenance of S&Cs in Sweden is presented. The research method and the data used for the investigation are

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[1] 1 Euro is around 11 SEK or Swedish crowns (kr).

described in Section 4 and Section 5, respectively. The modelling results are presented in Section 6. Section 7 gives an LCC calculation example, followed by a discussion in Section 8. Finally, Conclusions are provided in Section 9.

2 Literature review

Studies on the long-term maintenance planning of S&Cs are reviewed below, with a focus on literature that adopts econometric, mechanical, or monetary approaches. The section ends with a summary and discussion of the current research gap(s).

2.1 *Econometric and engineering approaches*

To improve the long-term planning of maintenance on critical assets such as S&Cs, it is important to evaluate and assess the relation between traffic and the costs of maintenance and renewal. In the current literature on optimal pricing of rail infrastructure usage, two main approaches are used to assess the link between traffic and infrastructure costs, namely econometric (below referred to as "Top-down methods") and engineering approaches (below referred to as "Mechanical engineering methods") (Link and Nilsson, 2005). Figure 1, adapted from (Odolinski et al., 2023), illustrates the main differences between the engineering approach and the adopted econometric approach (combined with LCC analysis).

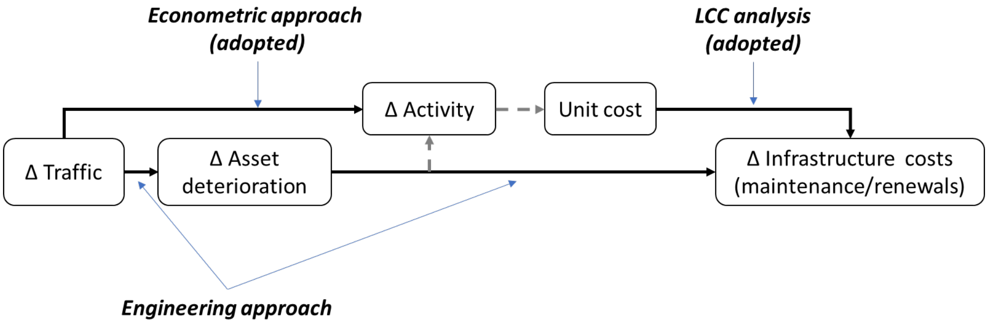

Figure 1. Econometric versus engineering approach to establish a relationship between traffic and infrastructure costs, adapted from (Odolinski et al., 2023)

In addition to these two approaches, so-called cost allocation methods (see a brief overview by Wheat et al. (2021)) based on economic assessments using lifecycle costing are also common in the literature (Nissen, 2009a, Zoeteman, 2001). Although other approaches are available (see a comprehensive review by Elkhoury et al. (2018)), the following review focuses on literature adopting one of the three approaches mentioned above.

Econometric (or top-down) methods directly relate the maintenance and/or renewal costs to the train traffic while controlling for (or assessing the impact of) other aspects such as infrastructure characteristics and asset condition (Smith et al., 2017). Examples are Johansson and Nilsson (2004), (Wheat and Smith, 2008), and Wheat et al. (2009).

Bottom-up methods adopting the engineering approach often include more steps, e.g., mechanical asset deterioration that is inflicted by different types of vehicles, and their impact on maintenance activities and costs (Smith et al., 2017). For S&Cs, several studies have focused on long-term asset deterioration using simulation tools, but the results have not been linked to maintenance activities and costs. For instance, Li et al. (2014) and more recently Six et al. (2021) use mechanical simulations of the track settlement in S&C turnouts to predict the accumulated settlement under traffic loading. Similarly, with a focus on the degradation of the crossing component, the dynamic interaction between wheel and rail has been studied using finite-element methods (Wei et al., 2017). In more recent research, Jorge (2020) proposes a calibrated computational model of S&Cs. Based on on-site measurements and performance assessment, the engineering-based model allows for redesigns that improve the resilience of the asset.

These engineering-based methods can capture the existing interactions' complexity and may help determine which maintenance activity can best remedy specific damages, e.g., tamping and/or grinding. However, when used alone, bottom-up methods have problems with the monetary conversion of damage estimates (Smith et al., 2017). They also need detailed information about the asset and calibration of damage models to make accurate predictions. Their primary strength lies in the capacity to study the interaction between different damage modes and make relative comparisons between track designs and maintenance regimes. In contrast to top-down methods using actual costs, the derived costs from bottom-up methods often reflect the need for maintenance and renewal in an ideal world (Link and Nilsson, 2005).

2.2 *Lifecycle costing*

Lifecycle costing is a commonly used approach in the literature to study the effectiveness of maintenance strategies by calculating their lifecycle costs (LCCs). It is an economic analysis of the different phases of an asset's lifecycle, i.e., acquisition (design and development, manufacturing, installation), ownership (operation and maintenance) and dismantlement at the end of its technical lifetime (Sasidharan et al., 2020).

Thus, lifecycle costing can provide an assessment of the effectiveness of certain decisions such as maintenance strategies. The approach can be used to study the infrastructure management of railway systems in general, see (Zoeteman, 2001), (Rama and Andrews, 2016) and (Elena, 2021). It can also be used with a focus on specific assets such as rail tracks (Patra, 2007), ballast (Sasidharan et al., 2020) or bridges (Han, 2017) and S&Cs (Nissen, 2009b).

Based on an LCC calculation, Zoeteman (2001) presents a concept for a decision-making tool for quantitative analysis of the long-term impacts of maintenance decisions. The approach was applied to a new Dutch high-speed line project. By combining data from different phases (construction, maintenance, operations, etc.), the author estimates LCC, including costs related to infrastructure reliability and availability. These aspects are often considered as part of the so-called RAMS analysis, i.e., Reliability, Availability, Maintainability and Safety. For instance, Patra (2007) presents how LCC can be combined with such analysis for improved maintenance planning of rail tracks. Other approaches can also be combined with LCC such as Cost-benefit analysis or CBA (Elena, 2021).

Focusing on the maintenance of S&Cs, Nissen (2009a) investigates maintenance activities and their corresponding maintenance costs using LCC modelling. The author studies data from automatic asset condition monitoring and how maintenance designs and decisions can be improved. The same author presents an application of the LCC model to S&Cs in the Swedish railways including costs for phasing-out as well as for different corrective and preventive maintenance activities such as tamping and grinding (Nissen, 2009b). The results help find cost drivers (e.g., crossing components for S&Cs) and provide a cost comparison of different types of S&Cs. Similarly, Vitásek and Měšťanová (2017) compare the LCC of four different types of S&Cs for the modernization of a Czech railway station. In addition to the operation and disposal costs, their model includes investment costs which, according to the authors' data, account for more than half of the total LCC.

Assets, such as the crossing panel, have a typical lifetime of several years. The costs in LCC models are therefore generally discounted to calculate the so-called total present value (TPV) using a specific discounting rate r which has been shown to have a significant impact on the resulting assessment (Asplund, 2019, van der Weide et al., 2010). The discounted yearly costs are summed over the lifetime of the studied asset(s). The TPV can furthermore be split into a yearly cost using the so-called annuity (noted ANN), i.e., the average yearly total discounted LCC.

2.3 *Summary and discussions*

The review of the existing related literature focuses on research studying rail infrastructure assets which adopts one (or a combination) of three different approaches, namely econometric, mechanical and lifecycle costing. An overview of the reviewed studies is given in Table 1 showing the studied rail infrastructure asset or component as well as the adopted research method(s).

Studies of more specific components, such as the crossing panel, often adopt engineering-based approaches whereas lifecycle costing is adopted in research focusing on more general infrastructure management. Recently, econometric approaches have been combined with engineering-based methods to study rail tracks, e.g., for more accurate marginal cost estimation of track access charges after vertical separations in European railway markets (Nash et al., 2018).

Table 1. Comparative summary of the reviewed literature

		Approach (X if yes)		
Reference (chronologically)	Assets/component	Econometric	Mechanical	Lifecycle costing
Patra (2007)	Rail tracks			X
Wheat and Smith (2008)	Rail infrastructure	X		
Nissen (2009b)	S&Cs			X
Li et al. (2014)	S&Cs		X	
Wei et al. (2017)	Crossing panel		X	
Smith et al. (2017)	Rail tracks	X	X	
Jorge (2020)	S&Cs		X	
Six et al. (2021)	S&Cs		X	
Smith et al. (2021)	Rail tracks	X	X	
Elena (2021)	Rail infrastructure			X
This paper	Crossing panel	X	X	X

Based on the reviewed research, few studies use top-down/bottom-up methods to investigate the long-term planning of specific rail asset components such as S&Cs and crossing panels. None of the studies combines these methods with an analysis of the LCC of maintenance and/or renewal of the assets. This research aims at using both methods, including an LCC calculation example for evaluating long-term maintenance planning of crossing panels.

3 Maintenance of S&Cs in Swedish railways

Relevant terminology is introduced below together with a general overview of S&C maintenance in Sweden.

3.1 Models and components of S&Cs

S&Cs are typically separated into three overall parts (or panels), i.e., switch, closure and crossing panel, see Figure 2. These are made up of different components, e.g., switch blades and switch drives in the switch panel, and crossing and check rail in the crossing panel of which some can be further divided into sub-components. For instance, the crossing panel, which is the focus of this study, includes frog/V-rail and crossing nose. The type and design of a S&C are indicated by its notation. For instance, UIC60-760-1:15 refers to an S&C with a UIC60 rail profile, 760-meter radius and 1:15-sharing angle (Risberg and Mitropoulos, 2008).

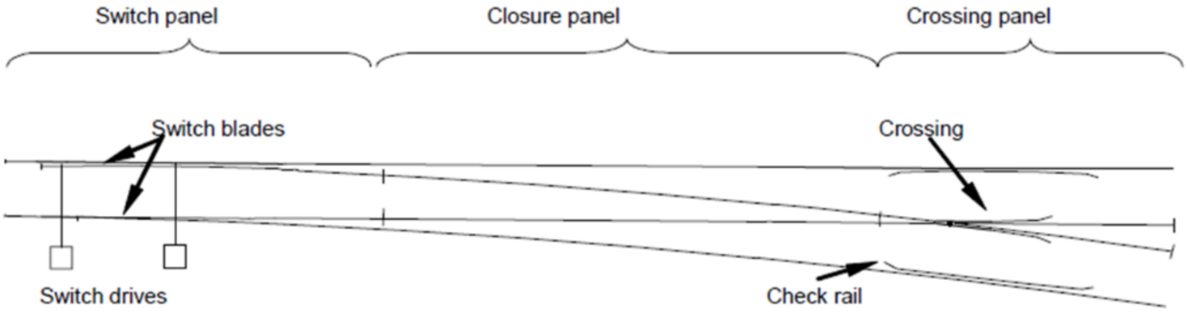

Figure 2. Illustration of the main panels and components of a standard turnout switch (Nissen, 2009a)

The large magnitude dynamic wheel-rail contact forces developed at the switch blades of the switch panel and the frog and crossing nose of the crossing panel make them particularly exposed to mechanical degradation, see Figure 2. This is especially accentuated for high-intensity freight traffic (Zwanenburg, 2007).

Figure 3 shows a timeline of the renewal year of all existing generations/rail profiles of S&Cs in Trafikverket's rail infrastructure as of 2020. The successive introduction of new generations of S&Cs is noticed, e.g., the older type UIC60 (yellow) currently is replaced by the more recent 60E (dark blue) which is studied here. Moreover, the age of the installed S&Cs is observed to vary substantially, where periods with a high number of renewals (e.g., 1994-1996) may lead to an increased need for maintenance and renewal within a future period, *ceteris paribus*. This need can often be noticed when infrastructure failures occur and therefore disruptions and delays become more frequent.

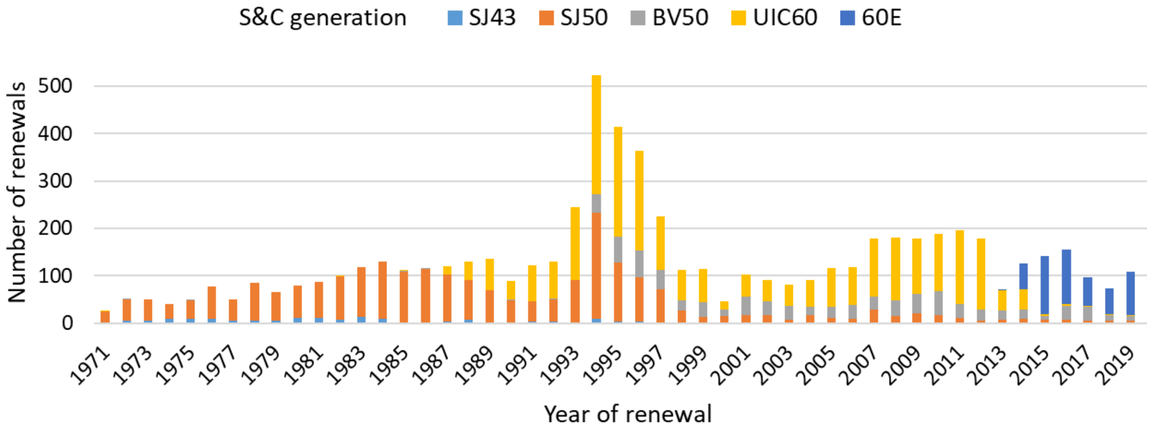

Figure 3. Distribution of S&C generations in Swedish railways including the newest generation 60E (based on BIS[2]-data from 2020)

3.2 *S&C-related infrastructure failures and delays*

As infrastructure assets get older, failures in S&Cs become more frequent and may therefore cause traffic disruptions (Zwanenburg, 2007). This subsequently leads to delays for passengers and freight customers. Infrastructure failures are one of the main causes of disruptions in Swedish railways. Between 2017 and 2018 alone, such failures accounted for around 17% of the total accumulated delays (Kristoffersson, 2019). During the same year failures in S&Cs increased by 38%. A third of these failures caused traffic disruptions (Hägglund and Jonsson, 2019).

Focusing on the main components of S&Cs, Figure 4 shows the reported disruptions and delays that were (reportedly) caused by S&C-related failures between 2014 to 2020 (0felia[3] database). The main S&C (sub-)components are sorted on the horizontal axis by the number of affected trains. The highest number of disruptions and disturbed trains are noticed to be caused by failures in switch panels and drives. Although few disruptions are caused by failures in the crossing panel, these lead to one of the highest average delays (around 350 minutes[4]) per failure (see Figure 4) and one of the highest numbers of affected trains (around 15,000 trains). Hence, these disruptions generate substantial socio-economic transportation costs. This indicates the need for a well-planned mix of maintenance activities, i.e., which can mitigate costly failures and traffic disruptions.

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[2] BIS data is a register for all infrastructure assets in the Swedish railway network.

[3] 0felia is a database which includes information about infrastructure-related failures such as time of the failure, train disruptions and delays, asset and components causing the failure.

4 Delay minutes are calculated based on an increase of at least 3 minutes delay. It is locally referred to as additional delay minutes.

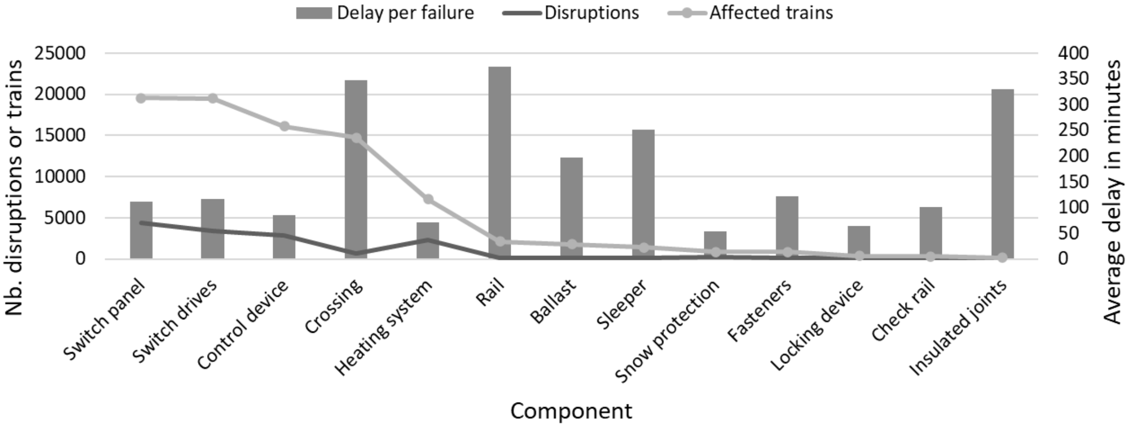

Figure 4. Reported disruptions and delays caused by S&C components in Swedish railways (based on 0felia[3] data between 2014 and 2020)

3.3 *Planning of maintenance activities on S&Cs*

Maintenance of assets, such as S&C, is generally based on the idea that actions should be taken when their quality is lower than a certain minimum threshold. Monitoring the quality or state of the asset requires regular inspections (Zwanenburg, 2007). To determine the frequency of inspections, Trafikverket separates the railway network into different classes (or inspection categories) depending on, e.g. traffic density and type, vehicle speed (Stenström et al., 2016). Parts of the track network that carry traffic with large speeds and/or trainload are likely to be more prone to failures which may cause costly disruptions and these parts are therefore inspected more frequently. For instance, there are up to 6 inspections per year of S&Cs with vehicle speeds above 140 km/h and/or a trainload over 8 million gross tonnes (MGT) per track and year (Stenström et al., 2016).

Figure 5 presents the distribution of the main maintenance activities carried out when an S&C-related failure occurred between 2014 and 2020. These data comprise performed corrective activities following an S&C component failure (reported in the 0felia database). Around 15% of reported failures are unknown or/and not associated with any S&C component.

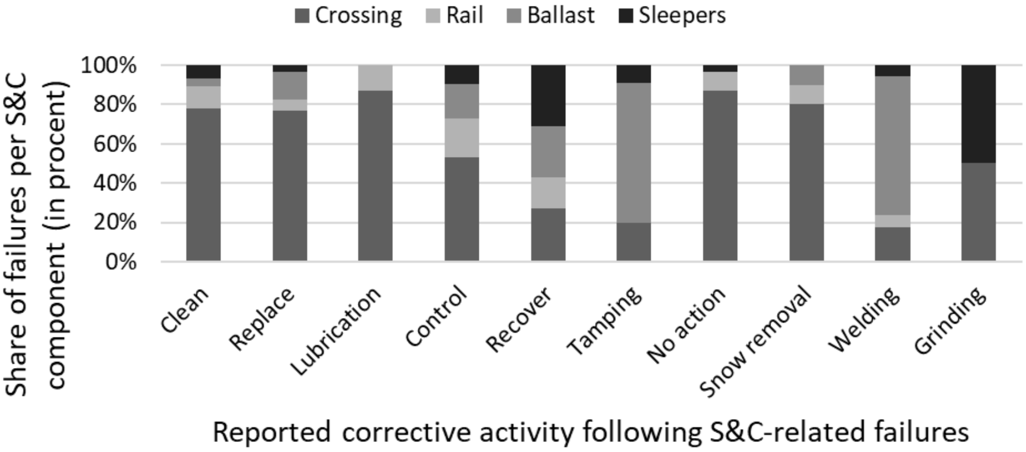

Figure 5. Share of reported maintenance activities carried out following failures in an S&C component (based on 0felia data between 2014 and 2020)

Inspections and maintenance are carried out throughout the lifetime of assets such as S&Cs. This translates into a total cost, which will vary depending on the adopted maintenance strategy. Lidén

(2019) finds, in an analysis of S&C-related maintenance costs, that the total costs between 2015 and 2017 were on average 380 million SEK, i.e., an average spending of 92 thousand SEK per S&C.

In addition to direct costs for maintenance, preventive/corrective activities lead to capacity costs since they both require access to the tracks (Hedström, 2020). Scheduled preventive activities are generally planned and carried out as part of maintenance windows in the timetable, which is often during off-peak hours to reduce their effect on traffic (Lidén, 2018). Moreover, these activities are often batched and therefore carried out at the same time over several parts of the infrastructure to reduce downtimes (or times during which infrastructure is unavailable). Unplanned corrective activities are, however, potentially causing delays and disruptions, especially for urgent repairs (Stenström et al., 2016). To summarize the main differences between preventive and corrective maintenance activities, Table 2 provides a comparative overview of some additional characteristics in terms of the planning horizon, knowledge requirements and traffic loss.

Table 2. Comparative overview of proactive and reactive maintenance strategies

Characteristic	Proactive or preventive	Reactive or corrective
Planning horizon	Medium to long term	Short-term (e.g., within two weeks)
Requirements	More knowledge about the assets	No knowledge is required
Traffic effects	Pre-planned and less expensive losses of traffic	Unplanned and more expensive losses of traffic and potential delays

Figure 6 presents the yearly distribution of preventive/corrective maintenance activities on the crossing panels between 2014 and 2019. It has been obtained by combining 0felia and Bessy[5] data for S&Cs. All activities that are performed within two weeks, as in Table 2, are considered corrective. As shown in Figure 6, around 80% of the maintenance activities are thus considered preventively planned, i.e., the planning horizon is longer than a month, whereas the remaining 20% can be considered corrective. The total number of performed activities increased until 2016 after which it stabilized at around 3 000 activities per year. An increase in the number of corrective activities can be an indicator of an ageing infrastructure and/or ineffective maintenance strategy. Assets are renewed when the components reach their maximum technical lifetime. S&Cs are typically renewed after 35-45 years depending on their characteristics and traffic (Nissen, 2009b).

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[5] Bessy is a database where all the inspection remarks are reported including the date, asset, component, and the recommended condition-based maintenance activities to perform as well as its status.

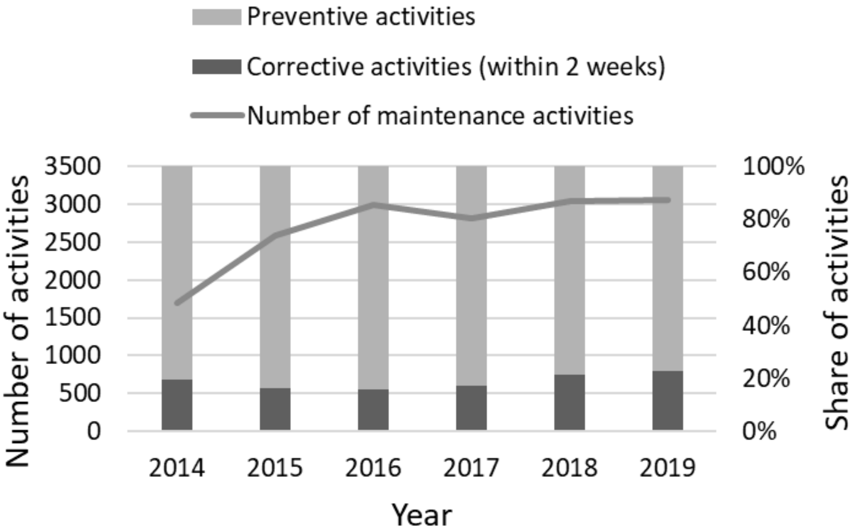

Figure 6. *Distribution of maintenance activities on crossing panels of S&Cs in Swedish railways between 2014 and 2019 (based on a combination of 0felia and Bessy data)*

4 Method

This section presents the method adopted by the current study, comprising both mechanical simulations and empirical analysis of maintenance activities. The purpose of the mechanical simulations is to provide a physics-based assessment of the long-term degradation of crossing panels for different maintenance regimes. This is to better understand the interaction between degradation mechanisms and maintenance activities. Due to the lack of long-term data for model calibration from the studied S&C, the simulation results can only support the empirical analysis with qualitative trends. The section ends with a description of the cost components in the LCC model which uses the empirical results to calculate the costs of long-term maintenance strategies.

4.1 Mechanical simulations

An iterative simulation scheme – comprising a multibody simulation (MBS) model combined with damage modelling – is used to model the long-term interaction between the crossing geometry condition and ballast settlement. In each step of the iterative scheme, the dynamic vehicle-S&C interaction is simulated using the MBS model followed by the calculation of a damage increment from the track response. The damage increment is added to the MBS model before the next step. The iterative scheme continues until the next maintenance activity or the end of simulations. The MBS model has 25 tons axle load and a finite element representation of the crossing panel that allows for a detailed output of the structural response of the track under traffic loading. The MBS model is described in (Milosevic et al., 2022).

In the MBS model, the crossing contact geometry is represented with a “gull wing” dip with a parameterised depth and therefore a dip angle that represents the vertical rail irregularity that wheels encounter as they roll over the crossing transition. The crossing dip angle is prescribed and increases linearly with the accumulated traffic load to represent crossing geometry degradation. This is a modelling simplification made to allow for the study of ballast settlement as a function of crossing geometry status over large, accumulated, traffic loads. To predict the damage evolution of a crossing in terms of plastic deformation and wear is otherwise a task that presently requires days of simulation time (Skrypnyk et al., 2021) per million gross tonnes (MGT). In practice, crossing geometries degrade faster initially when plastic deformation is the dominant source of crossing geometry change. Once the crossing nose has hardened and adapted to the passing wheels, the degradation is predominantly driven by wear and is more linear (Skrypnyk et al., 2021) until the crossing is very worn and experiences high-impact loads that exhaust the ductility of the material and accelerate the degradation process again, e.g., via material spalling.

The ballast settlement model is a truncated version of the threshold model from (Li et al., 2014) originally developed by Sato. The non-linear term is omitted as its influence is negligible for the ballast pressure magnitudes present in this study. The model predicts a settlement that is proportional to pressures that exceed a threshold. The settlement propagation coefficient is 1.33 e-8 [m/Pa] per 10,000 loading cycles as in (Li et al., 2014) while the pressure threshold for settlement is taken as the slightly lower 120e3 Pa compared to the 129e3 Pa in (Li et al., 2014). In the iterative scheme, the step size is limited to 100,000 cycles/2.5 MGT or 0.1 mm of settlement, whichever is smaller. Ballast maintenance in the simulation model is performed by resetting all settlements to zero and restarting from a new ballast state. The ballast settlement model is time-invariant as the propagation coefficient and settlement threshold are constant in time. The model, therefore, does not account for any change in ballast quality over time. Thus, a ballast reset most closely resembles a complete ballast renewal in practice even though it could also represent a tamping activity.

Using the iterative scheme, two main scenarios are studied. One where the crossing geometry is allowed to deteriorate to an extreme condition and one where the crossing is well maintained. The scenarios are illustrated in Figure 7. In the crossing degradation scenarios, the crossing geometry degrades linearly until the geometry is fully restored via crossing rail replacement or repair welding. The starting point of 6 mrad corresponds to a nominal crossing and wheel combination for a 60E1-1:15-R760 S&C and the extreme point of 24 mrad corresponds to the most worn crossing found in the crossing geometry scans performed in (Milosevic et al., 2022). This crossing was replaced shortly after with an estimated life of 90 MGT and had then been repair welded at least once during its life span.

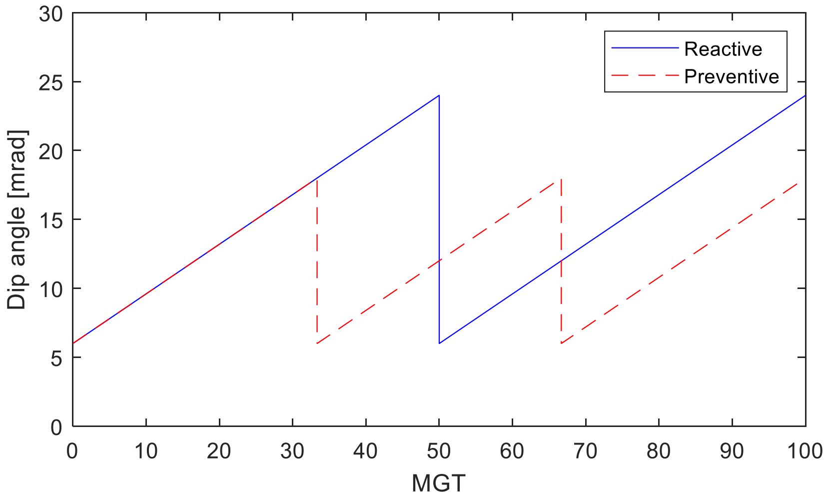

Figure 7. Crossing dip angle scenarios as a function of MGT for reactive and preventive maintenance.

The simulation methodology provides the ballast settlement evolution over time in the crossing panel for these two crossing maintenance scenarios. It is assumed that the ballast will be maintained when the sleeper displacement at the crossing reaches 3 mm or when the crossing is maintained or replaced. The simulations will therefore output the number of ballast maintenance actions (resets) needed under the two crossing maintenance scenarios.

4.2 *Empirical analysis*

Each S&C experiences an event (preventive or corrective activity) within a certain time. The time to this event (noted T) can be modelled using the survival function $S(t) = 1 - F(t) = P(T > t)$ which indicates the probability of surviving after t, where $F(t)$ is the cumulative distribution function of T. From this, we can obtain the hazard function which is the probability of an event in a certain time interval given that it has survived until that time. Specifically, the hazard function is formulated in equation (1).

$$h(t) = \lim_{\Delta t \to 0} \frac{P(t+\Delta t > T > t | T > t)}{\Delta t} = \frac{-dlnS(t)}{dt} \tag{1}$$

There are various approaches to modelling hazard functions, often categorized as non-parametric (e.g. the Kaplan-Meier or Nelson-Aalen estimators), semi-parametric (Cox proportional hazard regression), or parametric approaches, where the latter assumes a distribution of the outcome and specifies the baseline hazard function (see, e.g., equation 3 below). The Weibull distribution is often used in reliability analysis, mainly due to its flexibility (Wolstenholme, 1999). The following Weibull regression model is used in this paper:

$$h(t|\boldsymbol{x}_j) = h_0(t)exp(\boldsymbol{x}_j\beta) \tag{2}$$

where $h_0(t)$ is the assumed baseline hazard, which is defined in Equation (3) as

$$h_0(t) = pt^{p-1}exp(\beta_0) \tag{3}$$

Equation (2) can thus be written as $pt^{p-1}exp(\beta_0 + \boldsymbol{x}_j\boldsymbol{\beta})$, where p is the shape parameter that is estimated on the empirical data – using maximum likelihood – together with the scale parameter $exp(\beta_0)$ (influencing the failure distribution along the x-axis) and the $\boldsymbol{\beta}$ parameters for our included variables $\boldsymbol{x}_j$. With $p = 1$, the hazard is constant, whilst it decreases if $p < 1$ and increases if $p > 1$. It is expected that $p > 1$ in our case (and indeed in other cases where assets wear out).

The events (hazards) are either preventive maintenance (Model 1) or corrective maintenance (Model 2). Model 1 is used to predict the number of preventive maintenance activities as gross tons accumulate. Model 2 is used to establish a relationship between corrective maintenance and a cumulative measure of preventive maintenance, as well as with cumulative gross tons. In both cases, we calculate cumulative hazards, which for the Weibull model is presented in Equation (4).

$$\int_0^t h(u)du = t^p exp(\beta_0 + \boldsymbol{x}_j\boldsymbol{\beta}) \tag{4}$$

4.3 LCC model

The total lifecycle costs for a mix of maintenance strategies on S&Cs are formulated with a focus on costs for maintenance and traffic operations. Firstly, an overview of the main components of the LCC model is presented. Thereafter, each cost component is described and formulated in more detail.

Given a specific mix of maintenance activities on S&Cs, the following three different yearly costs in the total LCC are considered:

- Direct maintenance costs (noted DMC) account for maintenance work and material.
- Traffic capacity costs (noted TCC) are the losses in traffic capacity due to preventive/corrective maintenance.
- Traffic disruption costs (noted TDC) refer to the costs of delays in freight/passenger train service due to S&C-related infrastructure failures.

The LCC (over the lifetime) is discounted using a discounting rate r. The total present value (TPV) is the sum over all the years τ of the lifetime T of the studied asset, see equation (5). The TPV can be used later to calculate the annuity (ANN) which allows a comparison of the yearly costs of the different maintenance strategies.

$$LCC = \sum_{\tau=1}^{T} \frac{DMC_\tau + TCC_\tau + TDC_\tau}{(1+r)^{\tau-1}} \tag{5}$$

Note that although not included in Equation (5), the total LCC may depend on the adopted maintenance strategy (e.g., the mix of maintenance activities) as well as other characteristics of the traffic and the infrastructure. The lifetime T in the equation indicates the year when the asset is renewed. This is commonly done after a certain trainload has passed, often expressed in MGT.

Direct costs for maintenance and renewal

The direct maintenance costs (DMC) for performing activities include both labour and material costs. The former depends on the time required to do the maintenance work (e.g., in hours) whereas the latter is a unitary cost per work activity. There are, however, some studies that report cost parameters for work on S&Cs, e.g., the labour cost of night/day maintenance work per hour (Lidén and Joborn, 2016).

With a focus on the crossing panel, Risberg and Mitropoulos (2008) report the material costs for renewal as well as for maintenance work on the component. In the European InnoTrack project, Ekberg and Paulsson (2010) perform an LCC analysis using (and reporting) average cost estimates for the yearly inspection, for grinding and tamping maintenance activities as well as for the renewal. Such values are used later in the LCC calculation example (Section 7). Additional costs can also be included but data availability on the cost parameters is often limited.

Maintenance capacity

To perform maintenance work for both preventive and corrective activities, it is necessary to allocate capacity to ensure access to the track for maintenance workers. This translates into a loss in traffic capacity for both freight and passenger train services, i.e., traffic capacity costs TCC.

Capacity for scheduled preventive activities (including inspections) is allocated beforehand, e.g., as part of maintenance windows which are typically (ought to be) blocked during the night or outside traffic peak hours (Ait Ali and Lidén, 2022). This is to minimize the loss in potential train traffic that otherwise could have taken place (instead of maintenance). For corrective maintenance activities (performed within two weeks after failure has been detected), the most urgent work might require the capacity to be allocated even during the day or traffic peak hours. In this case, the traffic capacity costs (or opportunity costs) become higher. To calculate such costs in terms of lost traffic production, we use, as in (Ait Ali and Lidén, 2022), the socio-economic valuation of the corresponding train paths. Such valuations are often used by Trafikverket (2020b) for conflict resolutions in the capacity allocation process.

Given a maintenance activity that is affecting N_k train paths of type k, the costs TCC can be formulated as in Equation (6)

$$TCC = \sum_k N_k(\mathrm{Time}_k \times (100\% + K_k) \times (100\% + J_k) \times B_k + \mathrm{Distance}_k \times C_k) \tag{6}$$

where B_k and C_k are, respectively, time and distance cost parameters for excluding a path of train type k.

Time_k and $\mathrm{Distance}_k$ are, respectively, the travel time and distance of the cancelled train path. The percentage parameters K_k and J_k are used to account for the exclusion of train paths of type k. These refer to the correction factor for the base time and the utility threshold of the train path, respectively. For more details on these cost parameters, see (Trafikverket, 2020b). The cost parameters in Equation (6) depend on the type k of the train service whose path is cancelled.

Table 3. Parameter values for train path cancellation of different types of train services (Trafikverket, 2020b)

	Cost parameters			
Type of traffic k	B_k (SEK/min)	C_k (SEK/km)	J_k (%)	K_k (%)
Commuters in large cities	1,238	104	15	20
Intercity (higher speed)	816	71	20	6
Freight (higher speed)	269	61	15	2

Table 3 presents parameter values for three different types, namely commuter and intercity passenger trains and freight services. Note that since travel time and distance are required for the cancelled train paths, an average value for the different types of traffic is used.

Traffic disruptions

When infrastructure-related failures occur, train services may be delayed while corrective measures are taken to restore the traffic. This leads to traffic disruption costs TDC which account for uncertainty and discomfort for both passengers and freight operators.

Traffic disruption costs are quantified using the socio-economic guidelines by Trafikverket (2020a). The corresponding costs can be calculated using the formulation in Equation (7) where for each train type k, D_k is the average delay, N_k is the number of delayed services, and C_k is the cost parameter for delays.

$$TDC = \sum_{\mathrm{k}} N_k D_k C_k \tag{7}$$

Current guidelines by Trafikverket (2020a) estimate one hour of delay to cost up to 282 SEK/person for passenger traffic and around 3.85 SEK/ton for freight traffic. Note that since these cost parameters are per trainload (person or ton), an average trainload for all delayed passenger and freight trains is assumed.

5 Data

Data on preventive and corrective maintenance activities, S&C characteristics, traffic, and inspection categories have been retrieved from Trafikverket. This includes information on which part of the S&C that have been subjected to maintenance activities. Keywords in the inspection reports have been used to allocate events to different S&C components.

Only S&Cs located on main railway lines are included in the dataset. This is because traffic information is only available for these tracks. Traffic data is restricted to the years 2014-2018 and hence the econometric estimations in this work consider this period.

Corrective maintenance refers to activities classified as urgent (often after inspections), requiring attention within two weeks. Preventive maintenance in our dataset comprises condition-based activities and are taken as activities carried out after two weeks or more.

In Section 6.2, the hypothesis that a higher number of cumulative preventive maintenance activities implies fewer corrective activities, *ceteris paribus*, is tested. This requires information on preventive maintenance carried out since the installation of an S&C. The available dataset contains this information from 1 January 2014 and hence this date serves as a starting point for the econometric estimations of this work[6].

Two different measures of cumulative preventive maintenance are considered:

1. A cumulative number of activities over the observed time period.
2. A cumulative number that restarts one day after a corrective maintenance activity.

Measure 2 is labelled ‘semi-cumulative’.

5.1 Descriptive statistics for econometric analysis

The sample includes 392 S&Cs observed during the years 2014–2018, generating 461,971 daily observations. Some of the S&Cs are installed later than 2014, which implies that we do not observe

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[6] Note that the exact date the S&C is installed is not available, which means that the calculated cumulative gross tons are higher than the actual cumulative gross tons (calculation starts 1 January the year the S&C is installed). This is the case for all S&Cs. Hence, on average, it is assumed that the overestimation of cumulative gross tons is similar across the sample.

all S&Cs during the entire period 2014–2018, i.e., the panel is unbalanced. Descriptive statistics are presented in Table 4. Note that the maintenance variables only cover activities on the crossing panel.

Table 4. Descriptive statistics per switch (392) per day 2014–2018. 461,971 daily obs. (unbalanced panel)

Variable	Mean	Std. Dev.	Min	Max
Maintenance, crossing panel				
Corrective activities per day	1.6E-04	0.013	0	1
Corrective activities — failure causing train delay (per day)	5.6E-05	0.008	0	1
Preventive activities per day	7.3E-04	0.027	0	1
Cumulative preventive activities per day	0.613	1.331	0	11
Semi-cumulative preventive activities per day	0.537	1.226	0	11
S&C characteristics, traffic, inspections				
Year S&C installed	2015.224	1.127	2014	2018
S&C age, years	2.389	1.236	1	5
Switch type EV-60E-760-1:15, dummy	0.212	0.409	0	1
Million gross tons (MGT) per day	0.025	0.023	0	0.198
Cumulative MGT	14.963	18.887	0	134.772
Inspection category 1, dummy	0.012	0.108	0	1
Inspection category 2, dummy	0.066	0.249	0	1
Inspection category 3, dummy	0.291	0.454	0	1
Inspection category 4, dummy	0.477	0.499	0	1
Inspection category 5, dummy	0.135	0.342	0	1
Unknown inspection category, dummy	0.019	0.136	0	1

The dummy variable for EV-60E-760-1:15 indicates that this switch type is quite common in our estimation sample (mean value 0.212).

The inspection category determines the number of safety inspections carried out per year. Category 1 implies one inspection per year, whilst categories 2 and 3 imply three and four inspections per year, respectively. Categories 4 and 5 imply six inspections per year.

5.2 *Combining databases for selecting S&Cs for mechanical simulations and LCC*

To perform mechanical simulations (and LCC calculations), the available data is analysed to select an S&C of interest that can be used as a case study. For that, the different databases (Bessy, 0felia, Lupp and BIS) are combined (or reconciled) to link information about the same S&Cs that exist in the different databases, as illustrated in Figure 8. Although much can be automated in this process, e.g., using identifiers such as object/S&C numbers, substantial manual work is still needed, e.g., to clean up data, recategorize some free text (especially in 0felia), resolve inconsistencies, etc.

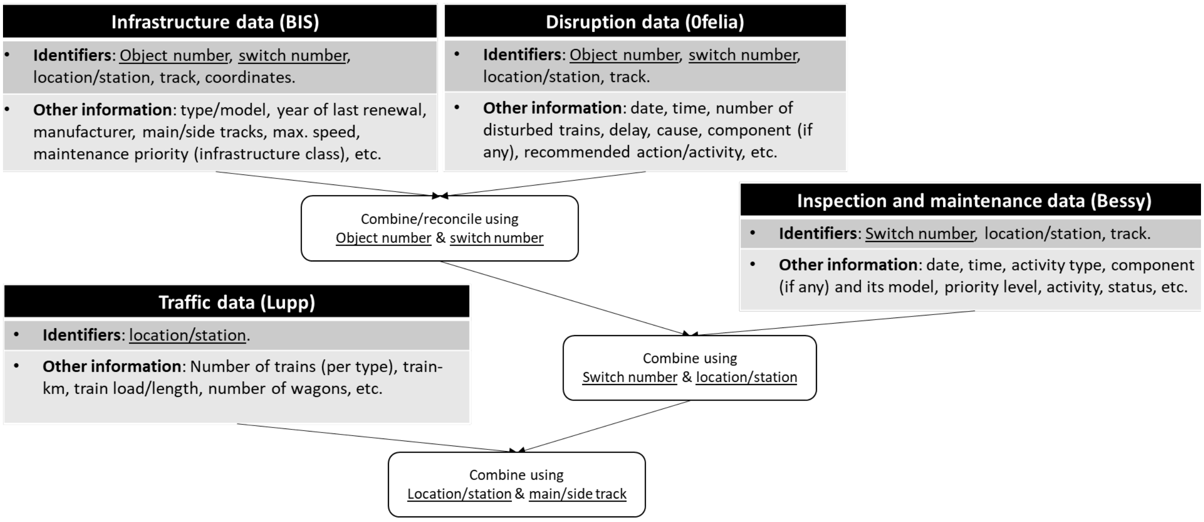

Figure 8. Sketch of how different datasets have been combined to create one complete dataset that contains all relevant information for each specific S&C

Since an S&C of type 60E-R760-1:15 is already available in the MBS software, it is chosen to restrict the data analysis to this type. Based on BIS data, there are around 109 S&Cs of this type in the railway network. As previously shown in Figure 3, most of these S&Cs were installed after 2014. Inspection (Bessy) data are available from 2014. To have the longest period of observations it is chosen to focus on the S&Cs that were installed in this year (2014). Further, traffic (Lupp) data are only available between stations and hence the analysis is restricted to S&Cs that are on the main track for more accurate estimation of the traffic flow, leaving around 9 short-listed S&Cs for further data analysis of delays, traffic, inspections, and maintenance.

Figure 9 illustrates some characteristics of the short-listed S&Cs. Note that all values have been rescaled/normalized into percentages where 100% and 0% refer, respectively, to the highest and lowest values of the short-listed S&Cs. 5 of the 9 S&Cs in the short-list contained extreme values (e.g. no observations) and are omitted from Figure 9.

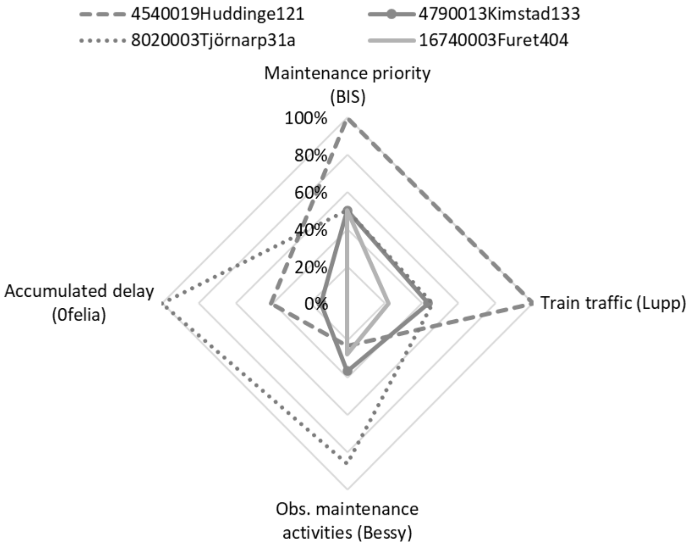

Figure 9. Examples of characteristics for selecting an S&C for mechanical simulations and LCC

Based on the previous data analysis, the S&C at Kimstad (identified by object number 4790013 and S&C number 133) seems to be a typical asset with no extreme characteristics (e.g., high/low traffic density, frequent/few disruptions, or delays). With an average yearly traffic load of 9 MGT, this

S&C is therefore selected for further analysis by mechanical simulations, econometric modelling as well as LCC in the following sections.

6 Modelling results

Below the main results from both the mechanical simulations and econometric modelling are presented. The calculations of LCC are found in Section 7.

6.1 MBS results: changing the type of maintenance activities

The accumulated settlements in the crossing panel are computed over 100 MGT for the scenarios in Figure 7. The resulting track degradation and crossing panel loading over this period is presented in Figure 10. From the results, several observations can be made. The dynamic impact load is, as expected, proportional to the prescribed impact angle evolution and the dynamic impact load increases monotonically between each crossing maintenance activity. The peak impact force levels correspond well to the simulated dynamic impact loads of (Milosevic et al., 2022) for scanned crossings. By studying the maximum ballast pressure, sleeper displacement and maximum void under the crossing panel sleepers it can be observed that the ballast has an initial "break-in" phase where settlements or voids are developed at locations in the sleeper-ballast interface with locally higher contact pressure. Thereafter the settlement and the voids grow slowly until about 35 MGT where the maintenance limit of 3 mm sleeper displacement is reached. At this stage, the ballast condition is reset in the simulation model for both maintenance scenarios and re-starts from a new ballast state. This ballast reset is closest to a full ballast renewal in practice but could also represent a tamping action. In the preventive scenario, the crossing geometry is reset as well corresponding to a crossing replacement or a full weld repair.

It can be observed that the track evolution diverges for the two maintenance scenarios after this point. In the preventive scenario, the track evolution is identical to the first cycle as both crossing and ballast were reset. In the reactive scenario on the other hand, the sleeper-ballast contact pressures are now very high under the loading of the degraded crossing geometry, and it takes just a few more MGT until the track has reached the maintenance limit again and needs further maintenance. This process continues at an ever-faster rate until the fully degraded crossing geometry at 24 mrad impact angle is reached after 50 MGT of traffic whereafter both ballast and crossing are reset. It should be noted that the ballast maintenance frequency predicted by the model is an extreme scenario and should only be interpreted qualitatively in that a more degraded crossing geometry should significantly increase ballast settlement rates. In an example from field measurements, it was found that the sleeper displacement under a 24 mrad crossing was 6 mm (Milosevic et al., 2022). The history of how quickly it got there was however not available.

Based on the simulation results, some effects can be expected to surface in maintenance history data with respect to the trade-off between preventive and corrective maintenance. The first is that frequent crossing geometry maintenance and replacement of crossings should lead to lower maintenance needs overall for the ballast, i.e., less of both planned and corrective maintenance. It can also be expected that more frequent crossing geometry maintenance should lead to less need for corrective maintenance in terms of broken crossing or sleepers due to the lower structural loading for a well-maintained crossing. One can also view the results the other way and conclude that frequently required tamping action can be an indication not only of poor ballast quality but also an excessively degraded crossing geometry.

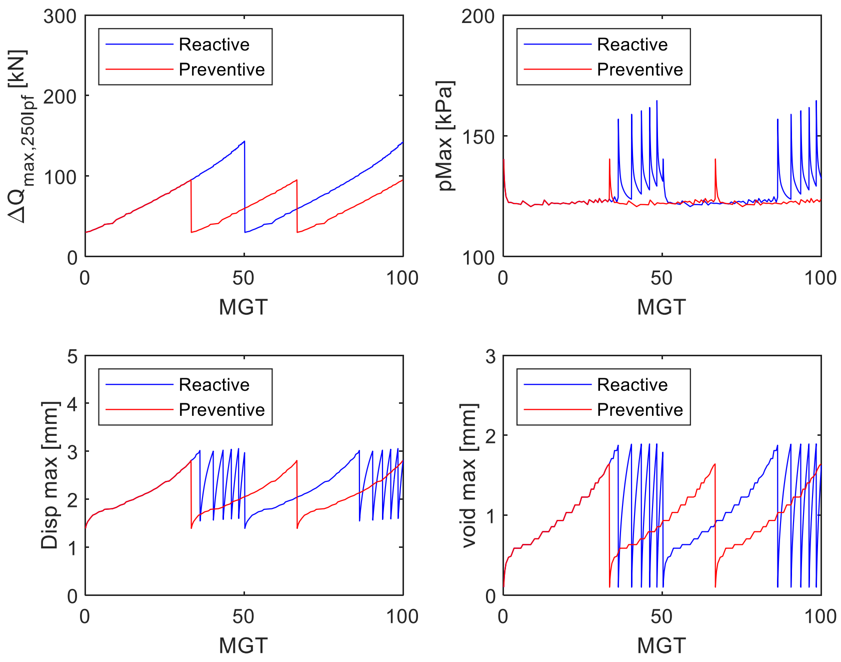

Figure 10. Evolution of settlements and crossing panel loading under two crossing geometry scenarios. Top left: Maximum dynamic impact load magnitude (total vertical force minus static wheel load) low pass filtered at 250 Hz. Top right: Maximum sleeper-ballast contact pressure in the crossing panel under a bogie passage. Bottom left: Maximum sleeper displacement in the crossing panel. Bottom right: Maximum void between sleeper and ballast in the crossing panel

6.2 Econometric results: changing the frequency of preventive maintenance

Estimation results are presented in Table 5. Cluster-robust (S&C-specific) standard errors are used since the outcomes may not be independent over time. Million gross tons (MGT), a dummy for switch type EV-60E-760-1:15 (same type as S&C 133 in Kimstad), month dummies and year dummies are used as explanatory variables for preventive maintenance (Model 1). MGT is log-transformed yet contains zero values. Following Gaudry and Quinet (2013), we handle this by including a dummy variable indicating observations with zero MGT (also the case for cumulative PM in Model 2).

A dummy variable for inspection categories 3–5 was not statistically significant (p-value 0.588) and therefore dropped in Model 1, whilst this variable has a large and statistically significant effect on corrective maintenance (Model 2).

Table 5. Estimation results, Weibull regression: Preventive and corrective maintenance

	Model 1 Preventive maintenance (PM) Coef.	Model 2 Corrective maintenance (CM) Coef.
Constant	2.899***	2.028
	(0.771)	(1.520)
ln(cumulative PM)		-0.951**
		(0.478)
D. zero cumulative PM		-1.165***
		(0.445)
ln(MGT)	1.265***	1.682***
	(0.250)	(0.497)

ln(MGT)^2	0.115***	0.131**
	(0.021)	(0.054)
D. zero MGT	-3.964***	-5.913***
	(0.708)	(1.288)
D. switch type EV-60E-760-1:15	-0.299	-1.269**
	(0.208)	(0.503)
D. inspection category 3-5		2.491***
		(0.960)
P	1.425	1.476
	(0.181)	0.477
1/p	0.702	0.677
	(0.089)	0.219
Month dummies	Yes	Yes
Year dummies	Yes	Yes
Log pseudolikelihood	-429.48	-176.021
No. of observations	461,971	461,971
No. of subjects	392	392
No. of failures	336	76

***, **, *: Significance at the 1%, 5%, and 10% level, respectively.
Cluster-robust standard errors in parentheses.

Cumulative hazards ($\int_0^t h(u)du = t^p exp(\beta_0 + \boldsymbol{x}_j\boldsymbol{\beta})$) for preventive maintenance activities on crossing panels are illustrated in Figure 11, indicating the differences between EV-60E-760-1:15 and other switch types in the dataset – note however that the dummy for EV-60E-760-1:15 is not statistically significant (p-value=0.151) and has a 95% confidence interval at -0.706 to 0.109. These cumulative hazards assume 9 MGT/year and are evaluated at sample means of the other explanatory variables (see Table 4). The predictions cover 15 years, and estimates after 5 years are extrapolations.

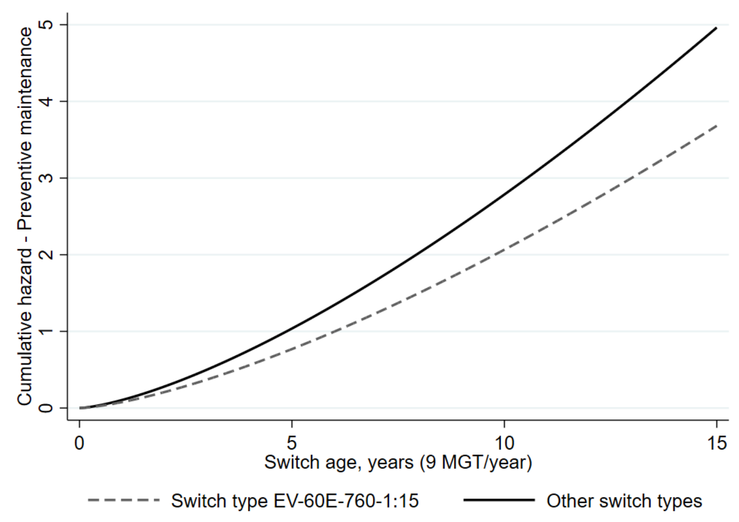

Figure 11. *Cumulative hazards for preventive maintenance – extrapolations from year 5.*

The parameter estimate for cumulative preventive maintenance (PM) in Model 2 has the expected negative effect on corrective maintenance and is statistically significant at the 5% level (p-value 0.047). Using semi-cumulative PM (restarts one day after a corrective maintenance activity) generates similar results. The negative relationship between cumulative preventive maintenance and corrective maintenance is illustrated in Figure 12 for switch type EV-60E-760-1:15, whilst

Figure 13 presents the corresponding results for other switch types. Similar to the cumulative hazards in Figure 11, the hazards are evaluated at the sample means of the covariates, except for MGT which is assumed to be 9 MGT/year.

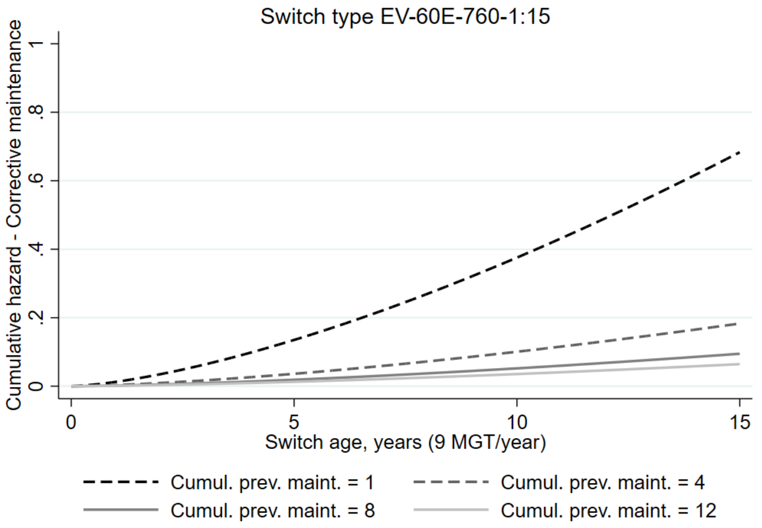

Figure 12. Cumulative hazards for corrective maintenance w.r.t cumulative preventive maintenance, switch type EV-60E-760-1:15 – extrapolations from year 5.

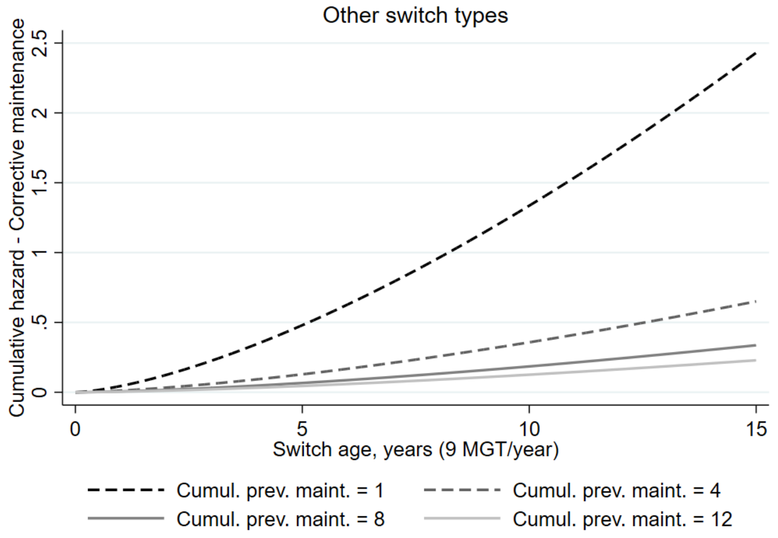

Figure 13. Cumulative hazards for corrective maintenance w.r.t cumulative preventive maintenance, other switch types – extrapolations from year 5.

Predictions of corrective maintenance activities on crossing panels, evaluated at the mean value of cumulative preventive maintenance and mean values of other covariates (see Table 4), are illustrated in Figure 14, indicating the general difference in corrective maintenance between EV-60E-760-1:15 and other switch types. The 95% confidence interval for the EV-60E-760-1:15 coefficient in Table 5 is -2.254 to -0.284, indicating a lower level of corrective maintenance on this switch type even at the upper limit of the confidence interval.

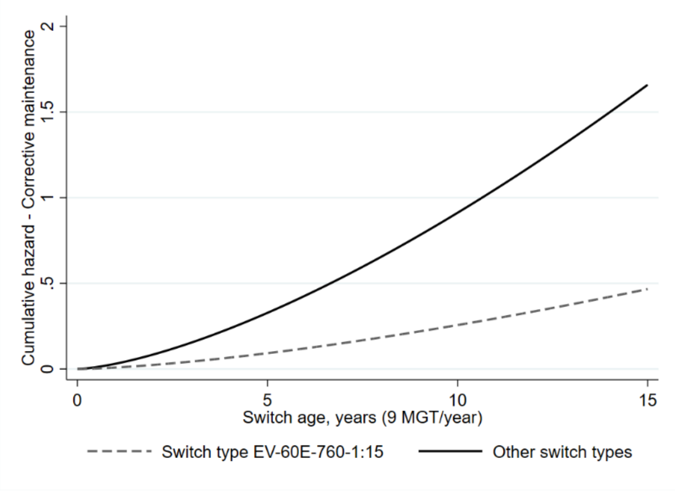

Figure 14. Cumulative hazards for corrective maintenance, EV-60E-760-1:15 compared to other switch types – extrapolations from year 5

7 LCC calculation: changing the mix of maintenance activities

Examples of lifecycle cost (LCC) calculations for different mixes of preventive and corrective activities are presented below. The focus is on the selected S&C at Kimstad and maintenance activities performed on the crossing panel of the asset.

7.1 Input data

Section 4.3 presents the adopted data for the calculation of the socio-economic costs, e.g., capacity and disruption costs. Table 6 presents a summary of additional input data that are used in the LCC calculations. It shows the input data, the adopted value and the unit as well as the reference. Since the selected S&C is on the Swedish Southern main line, some data in the table are specific to this line, e.g., average travel time/distance, and train ridership/load.

Table 6. Summary of input data for LCC calculations (2014 price levels)

Input data	Value (category)	Unit	Reference
Discounting rate	4	%	(Nissen, 2009b)
Traffic load	9	MGT/year	Lupp data
Train traffic	3 750 (freight) 8 500 (intercity) 8 500 (commuter)	Train/year	(Nelldal et al., 2019)
Train ridership/load	800 (freight) 298 (intercity) 282 (commuter)	Ton per train Passenger per train	(Nelldal et al., 2019)
Average travel time	3.33 (freight) 4.42 (intercity) 0.82 (commuter)	Hours	(Ait Ali and Lidén, 2022)
Average distance	450 (freight) 617 (intercity) 79 (commuter)	Kilometres	(Ait Ali and Lidén, 2022)
Maintenance costs	45 352	SEK per activity	(Ekberg and Paulsson, 2010)
Inspection costs	7 067	SEK per year	(Ekberg and Paulsson, 2010)
Renewal costs	319 922	SEK per renewal	(Ekberg and Paulsson, 2010)
Delay-causing failures	34	%	0felia data
Average delay	1.917	Hours per failure and train	0felia data
Average delayed trains	6	# per delay-causing failure	0felia data
Maintenance downtime	1.25 (corrective) 1 (preventive)	Hours per activity	(Ekberg and Paulsson, 2010)

7.2 Scenarios: two mixes of maintenance activities

S&C 133 in Kimstad include observations from its installation in 2014 until 2018. Examples of relevant event observations are (delay-causing) infrastructure failures, inspections, and preventive and corrective maintenance activities, e.g., tamping and grinding of the crossing panel. Since the LCC calculation example covers a period beyond 2014-2018, we distinguish between two different scenarios/mixes of maintenance activities (see Figure 15):

1. Mix 1 – investigation option: Adopted mix between 2014 and 2018 followed by a standard mix (from empirical analysis).
2. Mix 2 – comparison option: Standard mix from installation in 2014.

The results of the empirical analysis, presented in section 6.2, define a standard maintenance strategy (mix 2). This mix refers to the corrective-preventive maintenance strategy that has been typically used for S&Cs in the sample, i.e., a comparison option. To compare mix 2 with the currently adopted maintenance strategy at Kimstad, we study mix 1, i.e., the investigation option. The latter consists of activities that are observed/adopted between 2014 and 2018, the strategy follows thereafter the previously inferred standard mix 2. Figure 15 presents the adopted mix 1 (adopted between 2014-2018) and the inferred mix 2 and mix 1 (beyond 2018). The figure shows the number of yearly preventive activities. As shown in the figure, the inferred need for preventive maintenance increases over time, i.e., with a higher accumulated trainload (in MGT).

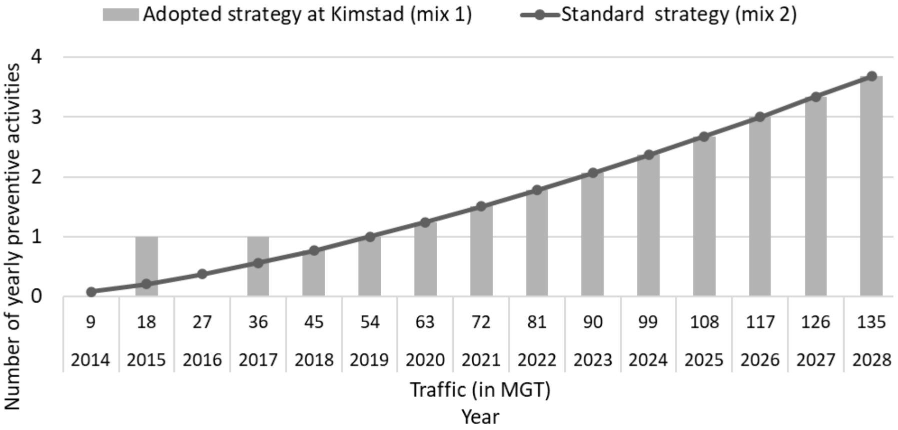

Figure 15. Variation of the average number of yearly activities for preventive maintenance in the two studied mixes on the crossing panel of the selected S&C at Kimstad

7.3 Results

The LCC calculated for the standard mix 2 of maintenance activities is shown in Figure 16. The total discounted costs as well as their share (in %) per year are presented. The different yearly costs (and their shares) are seen to increase from the renewal year (2014) until 2024 (or 99 MGT), see Figure 16. These costs are noticed to increase steadily due to the increased need for corrective maintenance and the corresponding socio-economic costs for capacity and disruptions.

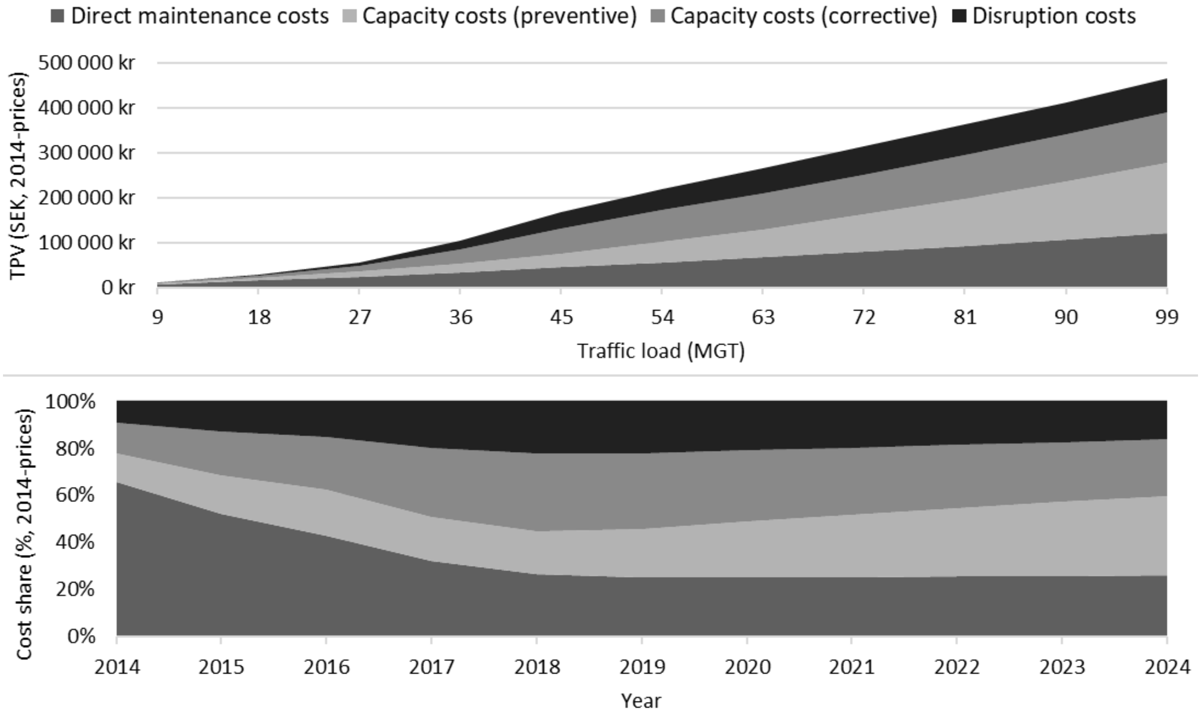

Figure 16. Results of LCC example calculation for the standard maintenance mix 2

The LCC costs increase over time due to the ageing asset with an increase in the need for both preventive and corrective maintenance as well as related caused disruptions. When the asset is old enough, the yearly costs can become substantially high, e.g., higher than renewal costs. At this stage, renewing the asset may seem to be cheaper than continuing maintenance, i.e., annuity (ANN) is higher than the renewal costs. Figure 17 shows how the annuity increases with more accumulated traffic load for the different mixes. For instance, for both mixes, renewal of the crossing panel should be performed after around 10 years since the last renewal in 2014, i.e., after 99 MGT of accumulated traffic load or in 2024.

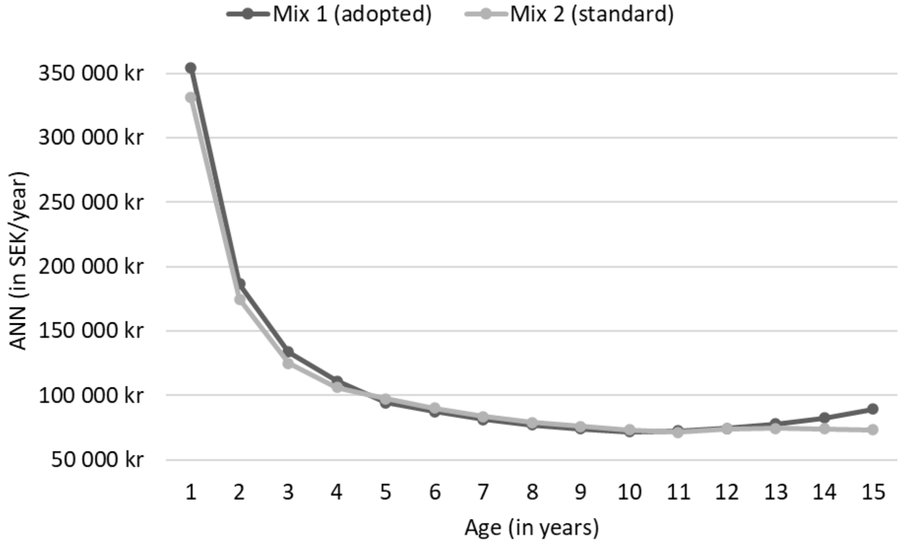

Figure 17. Renewal cost and annuity for different lifetimes in the different maintenance mixes

After the 10-year renewal plan, Table 7 presents the share of the different sub-costs in the ANN for the studied mixes. It indicates that the costs between 2014 and 2024 are slightly lower for the standard maintenance strategy (mix 2) which is less preventive (with a higher share of corrective and disruption costs) as compared to the adopted strategy (mix 1).

Table 7. Annuity (ANN) and the distribution of costs for the studied maintenance mixes on the selected S&C at Kimstad over the lifetime 2014-2024 in Swedish crowns kr.

	ANN	Maintenance (%)	TCC_{prev} (%)	TCC_{corr} (%)	TDC (%)	Renewal (%)
Mix 1 (Adopted)	71 640 kr	10 669 kr	13 136 kr	9 423 kr	6 419 kr	31 992 kr
	(100%)	(15%)	(18%)	(13%)	(9%)	(45%)
Mix 2 (Standard)	71 378 kr	10 990 kr	14 282 kr	10 125 kr	6 897 kr	29 084 kr
	(100%)	(15%)	(20%)	(14%)	(10%)	(41%)

7.4 Sensitivity analysis

A sensitivity analysis is performed to evaluate whether some variant of the standard mix is suitable for long-term maintenance of the studied asset at Kimstad. This is performed by calculating the annuity (10 years lifetime) for different variations of the standard strategy (mix 2), i.e., different increases/decreases in the percentage of the number of preventive activities of the standard mix. The variation of the annuity is presented in Figure 18 for different discrete variants of the standard mix, e.g., 0% in the horizontal axis corresponds to the standard whereas positive values (up to +50%) correspond to a larger share of preventive maintenance. All different costs over the lifetime between 2014 and 2024 are accounted for.

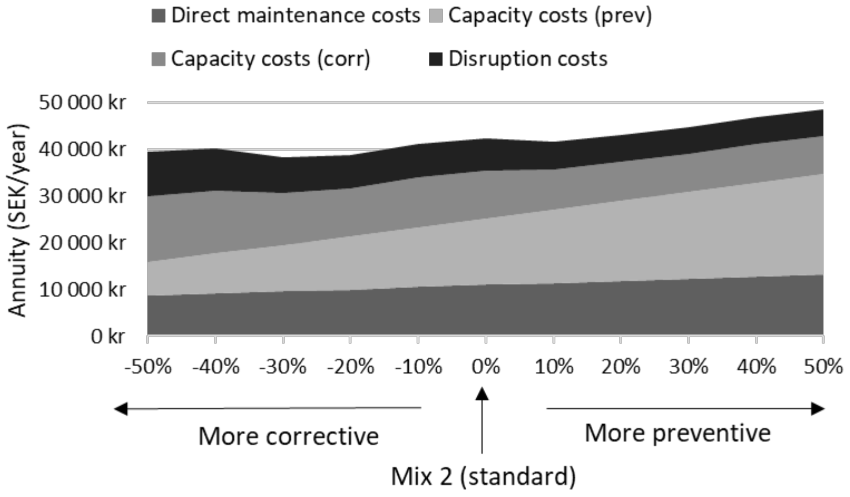

Figure 18. Annuity of different preventive/corrective variants of the standard maintenance strategy (mix 2)

Figure 18 indicates that the annuity is relatively robust to the variants of the standard mix, although a higher share of preventive maintenance seems to lead to a higher annuity, mainly driven by the increase in capacity costs for preventive activities. Thus, the lowest annuity is obtained for a 30% more corrective variant, however, the annuity is only 5% lower than that of the standard mix 2. The optimal annuity (and lifetime) is therefore almost invariant which can be an indication that the standard mix may seem to be a robust and suitable strategy for the maintenance of the studied asset.

The LCC calculation example illustrates how an assessment of the mix of maintenance activities can be performed. The LCC results and sensitivity analyses indicate that the standard maintenance mix, which was inferred based on regression analysis, may have led to the lowest annuity, and seems thus to pay off over the lifecycle of the selected crossing panel between 2014 and 2024. However, further analysis may be needed, e.g., to simultaneously consider the variation of the maintenance mixes over the lifecycle, and/or to distinguish between the different types of maintenance activities to perform (tamping/grinding).

8 Discussion

S&Cs allow for increased capacity of railway track networks and are therefore vital assets. However, if not well-maintained, they can lead to substantial direct costs for maintenance and renewals as well as additional transportation costs, e.g., capacity costs, traffic disruptions and delays. In Sweden alone, failures in the crossing panel of S&Cs (between 2014 and 2020) have led to costly traffic disruptions causing around 350 minutes of delay on average per failure, see Section 3.2 for more detailed statistics. This underlines the importance of developing improved maintenance strategies for S&Cs.

8.1 Highlights

This study integrates two commonly used approaches in the literature, i.e. mechanical simulations and econometric modelling, to analyse LCCs for different maintenance strategies of railway crossing panels. Mechanical simulations of long-term ballast settlement show a strong correlation with crossing geometry degradation. These results mimic observations from the field (Milosevic et al. (2022)) and indicate a need for preventive grinding or repair welding of the crossing panel geometry to avoid excessive ballast degradation and the associated need for corrective tamping activities.

The mechanical simulation results provide insights into degradation mechanisms and the interdependence between their associated maintenance activities (tamping/grinding). This can be used as the basis to assess the trade-off between preventive and corrective maintenance activities. The econometric modelling gives additional quantitative results on these trade-offs and in particular on their associated external effects such as traffic disruptions. For example, it is shown that an increase in preventive maintenance activities decreases the number of corrective maintenance interventions. Although studies on the relationship between these activities in practice are rare, Stenström et al. (2016) also highlight the importance of preventive activities in saving corrective (and total) maintenance costs.

The LCC analyses convert the quantitative results into annuities or total costs over the asset lifetime in order to compare different mixes of maintenance activities and find the optimal mix in terms of socio-economic efficiency. To illustrate this, a calculation example compares the standard mix (across all S&Cs) to the adopted mix at Kimstad. The LCC results indicate that the standard strategy/mix would lead to lower long-term costs as compared to the adopted one. The results also show that the economic lifetime of the crossing panel is around 10 years (or 99 MGT) which is similar to existing guidelines on technical lifetimes. Unlike (Stenström et al., 2016), the results of sensitivity analyses show that a maintenance mix containing fewer preventive interventions as compared to the standard mix could slightly reduce the total costs.

8.2 Contributions and limitations

The literature review in Section 2 indicates that few studies on long-term maintenance planning of S&Cs integrate econometric, engineering analyses, and lifecycle costing. Studies that evaluate the economic efficiency of different maintenance strategies are particularly rare. This paper contributes to filling this gap by presenting an example LCC calculation that compares different maintenance mixes to find the most economically efficient long-term maintenance strategy for the crossing panel of a selected S&C. Moreover, the work integrates qualitative results from mechanical simulations with quantitative results from an econometric analysis.

The econometric approach uses observations to infer interrelations between different events, e.g., preventive/corrective activities, and traffic disruptions/delays. This empirical analysis is complemented using results from mechanical simulations, providing examples of the mechanisms that could, at least partly, explain the relationship between preventive and corrective maintenance that is established by the econometric model.

Trafikverket as well as other infrastructure managers are instructed to integrate socio-economic efficiency in their long-term maintenance planning. However, there is a lack of tailored tools for decision-making which creates a demand for this branch of research. This also means that results have the potential to make a significant impact on the railway system. To be able to find economically efficient maintenance strategies, lifecycle costing convert earlier results into economic costs using existing socio-economic cost parameters. Total cost measures, e.g., annuities, are aggregated evaluations that allow for comparison between maintenance strategies/mixes with different economic lifetimes and therefore allow for decision-making from a socio-economic perspective.

Although the different approaches and their integration have large potential as explained earlier, some limitations are worth mentioning. For instance, empirical analysis is based on datasets of observations that cover a limited period of time (and space). The results may therefore be limited by the extent and quality of this data. Moreover, the preparation of such datasets, e.g., by matching different databases, may as in the current work involve a significant effort. However, guidelines and procedures for automated data collection are under rapid development which gradually will improve data access.

The computational time associated with running the mechanical simulations constitutes another limitation of the current study. However, increasing computational power, e.g., using super-computers, in combination with the development of reduced-order simplified engineering methods will gradually make these simulations more efficient. Additionally, the lifecycle costing is limited to a specific asset of the studied railway line. The study can therefore be generalized by simultaneously considering the maintenance of more assets, e.g., several S&Cs, on the same line.

8.3 Suggestions for further research

Several further extensions can be explored in future work. An obvious possibility is to combine the proposed LCC framework with data obtained from wayside and on-board monitoring systems in order to develop digital twins and support long-term maintenance planning. Such digital twins should allow continuous updating with respect to performance data collected from the field and hence provide digital representations that capture the gradual mechanical degradation of the assets including their root cause and interrelations between damage mechanisms.

Future work can also adopt a holistic perspective to account for larger sections of railway infrastructure in the LCC assessment. In a deregulated market for railway maintenance (as in Sweden), this can, for example, involve studying potential economies of scale and scope when dealing with larger infrastructure regions, e.g., areas within the same maintenance contract. Another related research is the optimization of maintenance windows and capacity allocation by identifying and synchronising optimal possessions to perform maintenance activities while minimizing traffic disruptions and optimizing capacity utilisation, especially on congested and highly utilised railway lines. Moreover, understanding how different assets interact and impact each other can also lead to more efficient and cost-effective maintenance practices.

The LCC model could be further used to analyse and identify cost-driving elements and parameters in the maintenance of railway assets. In-depth analyses can focus on a specific (or combination of) factor(s) that may significantly influence the total costs. These include, for instance, material quality, traffic loads, maintenance planning, and/or environmental conditions. Understanding the socio-economic effects of these factors can lead to more accurate cost predictions and develop targeted strategies for cost control and reductions.

9 Conclusions

The study combines results from mechanical simulations, econometric modelling and lifecycle costing to evaluate the cost-effectiveness of different maintenance strategies for the crossing panel of S&Cs. By doing this, it addresses the existing gap in the reviewed literature where few works combine these different approaches to analyse the impact of different maintenance strategies on vital assets such as S&Cs. Moreover, the research integrates mechanical and econometric modelling to investigate the interdependence between deterioration mechanisms, maintenance activities, and expected LCC which also includes transportation costs such as traffic disruption costs.

Based on a combination of different databases, the analyses focus on a selected key S&C in the Swedish infrastructure. The mechanical simulations provide insights into the degradation mechanisms of different maintenance (tamping/grinding) activities and a basis for the relationship between specific preventive and corrective activities. The econometric model offers a quantitative understanding of how variations in age (or traffic loads) and preventive maintenance strategies impact the need for corrective maintenance and the occurrence of traffic disruptions and delays. By conducting an LCC calculation example, this research illustrates how different maintenance mixes can be compared for more cost-effective long-term decision-making.

The main contribution of this work lies in combining qualitative insights from mechanical simulations and quantitative empirical results into a comprehensive LCC analysis, illustrating how the approach can be used for long-term maintenance planning of a specific asset component, e.g., the crossing panel of a S&C. The study emphasizes the importance of considering different socio-economic costs such as transportation costs from traffic disruptions. It also acknowledges certain limitations such as the limited temporal extent of the empirical datasets and the computational time for simulations.

The integration of digital twins and condition monitoring are highlighted as promising tools to investigate in future works. These can, for instance, lead to a more holistic understanding of degradation mechanisms and interdependencies between railway components. Future research could also explore better capacity allocation for maintenance possessions, and socio-economic effects of factors influencing maintenance costs to identify cost-driving parameters.

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